D1-82-0804

BOEING SCIENTIFIC RESEARCH LABORATORIES

Flight Sciences Laboratory

ON SHOCK-TUNNEL SIMULATION OF SCRAMJET COMBUSTION CHAMBER PERFORMANCE

by

J. Kenneth Richmond

R. J. Parsons

J. Swithenbank

November 1968

On Shock-Tunnel Simulation of Scramjet Combustion Chamber Performance*

by

J. Kenneth Richmond, Staff Member
Boeing Scientific Research Laboratories, Seattle, Washington

R. J. Parsons, Research Fellow,

and

J. Swithenbank, Senior Lecturer,
Department of Fuel Technology and Chemical Engineering,
University of Sheffield, Sheffield, England

Abstract

The combustion-driven shock-tunnel can supply flows with the static temperatures, static pressures, and velocities required for simulation of scramjet combustion chamber conditions for flight Mach numbers up to 15. Limitations of the shock tunnel include the difficulty of attainment of a steady, equilibrium flow of pure air, free of driver gas contamination. In the Sheffield University shock tunnel facility, a high speed sampling valve, probe, and gas analyzer were applied to the flow at the exit of a M = 3 nozzle, with stagnation pressure = 100 atmospheres and stagnation temperature = 6000°K, with coaxial hydrogen injection. Gas sampling indicated the early arrival of driver gas and depletion of oxygen, even without fuel injection (indicating formation of NO). The latter results are roughly verified by a non-equilibrium flow analysis.

* Work performed at the Department of Fuel Technology and Chemical Engineering, University of Sheffield. Supported in part by the Ministry of Technology, U. S. Air Force, and the Science Research Council.

On Shock-Tunnel Simulation of Scramjet Combustion Chamber Performance*

by

J. Kenneth Richmond, Staff Member
Boeing Scientific Research Laboratories, Seattle, Washington

Abstract

The combustion-driven shock-tunnel can supply flows with the static temperatures, static pressures, and velocities required for simulation of scramjet combustion chamber conditions for flight Mach numbers up to 15. Limitations of the shock tunnel include the difficulty of attainment of a steady, equilibrium flow of pure air, free of driver gas contamination. In the Sheffield University shock tunnel facility, a high speed sampling valve, probe, and gas analyzer were applied to the flow at the exit of a M = 3 nozzle, with stagnation pressure = 100 atmospheres and stagnation temperature = 6000°K, with coaxial hydrogen injection. Gas sampling indicated the early arrival of driver gas and depletion of oxygen, even without fuel injection (indicating formation of NO). The latter results are roughly verified by a non-equilibrium flow analysis.

* Work performed at the Department of Fuel Technology and Chemical Engineering, University of Sheffield. Supported in part by the Ministry of Technology, U. S. Air Force, and the Science Research Council.

Introduction

Although basic research into combustion and fluid mechanics may be done effectively independently of applications, wider interest is achieved if such research can be conducted under conditions resembling some interesting set of flight conditions. Ground-based tests continue to be important, not only because of the lower costs, but also because of recent cutbacks in proposed flight tests of scramjet engines.

Because of the enormous stagnation pressures required for hypersonic flight, in addition to adequate stagnation temperatures, completely integrated engine tests on the ground are very unlikely. Instead, it has become customary to perform tests separately for the performance of scramjet diffusers, combustion chambers, and nozzles, even though in a practical engine such clear distinctions are not likely.

Misleading results from faulty simulation can indicate erroneous combustion chamber shapes from failure to scale pressure as well as temperature. Three-dimensional effects may often shorten reaction lengths due to the production of radicals in recirculation zones. It appears that mixing predictions based on coaxial results may be optimistic compared to results with mixing from a strut, for example. The effects of initial profiles and boundary layer thickness have to be evaluated in order to scale mixing. Finally, the effect of heat release on mixing may have to be taken into account.

The emphasis in this report will be on how the state and composition of the test gas are simulated in shock tunnel tests. Even though impulse facilities such as shock tunnels and "hot shot" tunnels are the only ones which can simulate both enthalpy and pressure for super-

sonic combustion tests, it will be shown how they may fall short in other respects. Arc tunnels can simulate enthalpy, but not usually pressure nor ideal gas conditions. Pebble bed heated wind tunnels can supply very steady flows of ideal gas at adequate pressures, but cannot simulate temperatures for the hypersonic flight range.

The Shock Tunnel in Propulsion Research

The use of shock tunnels for aerodynamic tests in the hypersonic range is well known. They can simulate gas dynamic effects in the Mach number range from 6 to 20, for altitudes from 50,000 to 300,000 feet, for useful ranges of dynamic pressure. This range is also useful for hypersonic inlet studies, but we will not refer further to aerodynamic effects, for which, in general, temperature need not be simulated.

Less well documented is the application of the shock tunnel to supersonic combustion chamber simulation. Recent work includes those described in References 1 and 2, where combustion chamber conditions were to be simulated for flight Mach numbers in the range of 10-15. These works will be referred to again.

The central problem of shock tunnels is the attainment of steady flow of adequate duration, which, with combustion experiments, may be longer than is necessary for pressure measurements only. The usual way of extending the testing time is to use interface tailoring, but this puts restraints on the stagnation temperatures available. Another problem peculiar to shock tunnels is driver gas contamination, about which not much has been published, but which will be dealt with to a considerable extent later in this paper. The problem of equilibrium flow and test

gas composition is common to all high enthalpy facilities requiring considerable expansion.

Facility and Experimental Techniques

The experiments described below were performed on the high pressure shock tunnel of the Department of Fuel Technology and Chemical Engineering of the University of Sheffield. The shock wave was normally driven by combustion-heated helium, but could be driven by cold helium or hydrogen. Details of the construction and performance have been published previously.[2,5] Reflected shock pressures of about 100 atmospheres were normally obtained, with theoretical stagnation temperature in the range of 6000-7000°K, with combustion driving. Tailoring was obtained for a range of primary shock Mach numbers from 8-10.

All the experiments described herein were performed with an axisymmetric nozzle with an area ratio of 4, which will expand a perfect diatomic gas to $M = 3$. The test section operated as a free jet, with probes located in the jet core. Transducers were located so as to measure driver pressure, incident shock pressure 10.5 feet from the end wall, reflected shock pressure at the end wall, static pressure near the end of the nozzle, and sometimes pitot pressure in the jet.

The fuel injector consisted of an airfoil support located at the end of the shock tube, with a tube extending from the trailing edge through the nozzle throat, and well into the divergent portion of the nozzle. The fuel supply system was synchronized with the driver pressure, so that a constant flow of fuel was maintained for a short time during the nozzle flow time. The fuel flow was metered through an orifice, and fuel

pressures as well as all other pressures were recorded on multi-channel oscillographs. A swirl generator was placed inside the fuel injector tube for some of the experiments.

Gas Sampling System

In order to analyze the gas composition in the flow, a sampling probe was located near the nozzle exit, and attached to a high speed sampling valve. A photograph of the probe and valve assembly, located in the test section, is shown in Figure 1, and a drawing of the valve itself in Figure 2. The probe was made of beryllium copper, usually with a blunted tip because of the high temperatures it was subjected to. The valve, obtained from the British Petroleum Research Center, Sunbury-on-Thames, was of the poppet type, solenoid-driven. A flow of carrier gas (argon) was maintained through the valve. When the valve was fired with a capacitor, a small sample of test gas from the probe was injected into the carrier gas and carried to the analyzer. A small bleed hole was located in the probe near the valve seat so as to provide a rapid purge. The response time of the probe was less than 50 microseconds. The smallest consistent opening time of the valve was about 1.5 milliseconds. At a given voltage and capacitance setting, the sample size was proportional to the difference between the recovery and carrier gas pressures, and was also a function of the internal temperature. Only one sample per run could be taken.

The gas analyzer was a simple gas chromatograph which could separate oxygen and nitrogen from each other, and from the lighter gases. Hydrogen and helium could be separated only partially from each other, with

the longest column used. Nitric oxide and water vapor could not be analyzed. The valve fired automatically with the tunnel, and the analysis was recorded thereafter. A diagram of the shock tunnel with the fuel injection and gas sampling systems are shown in Figure 3. A complete description of the rapid sampling techniques used will be found in Reference 6.

Because sample size varied somewhat with tunnel conditions, and because NO and H_2O could not be analyzed, an absolute analysis of samples by the chromatograph was not possible. Instead, the analyses are reported here using nitrogen as reference. Calculations showed that, even under the most extreme conditions, the mole fraction of nitrogen in the air varied only by a few percent. On the other hand, the response of the detector was proportional to the mass of each component over a large range, according to the calibration. So peak heights obtained after sampling were used to estimate the size of the sample and to monitor the performance of the sampling valve when erratic behavior was suspected.

Shock Tunnel Flow Predictions

Reservoir conditions for the shock tunnel, for a real gas at equilibrium were calculated from the reflected shock data of Reference 7. Reservoir temperatures are plotted in Figure 4, and reservoir pressures (with experimental points) are plotted in Figure 5.

Using the above values for reservoir conditions, the state of the air in the nozzle, for both equilibrium and nonequilibrium flow, was calculated from the data of Reference 8. Area ratio is plotted

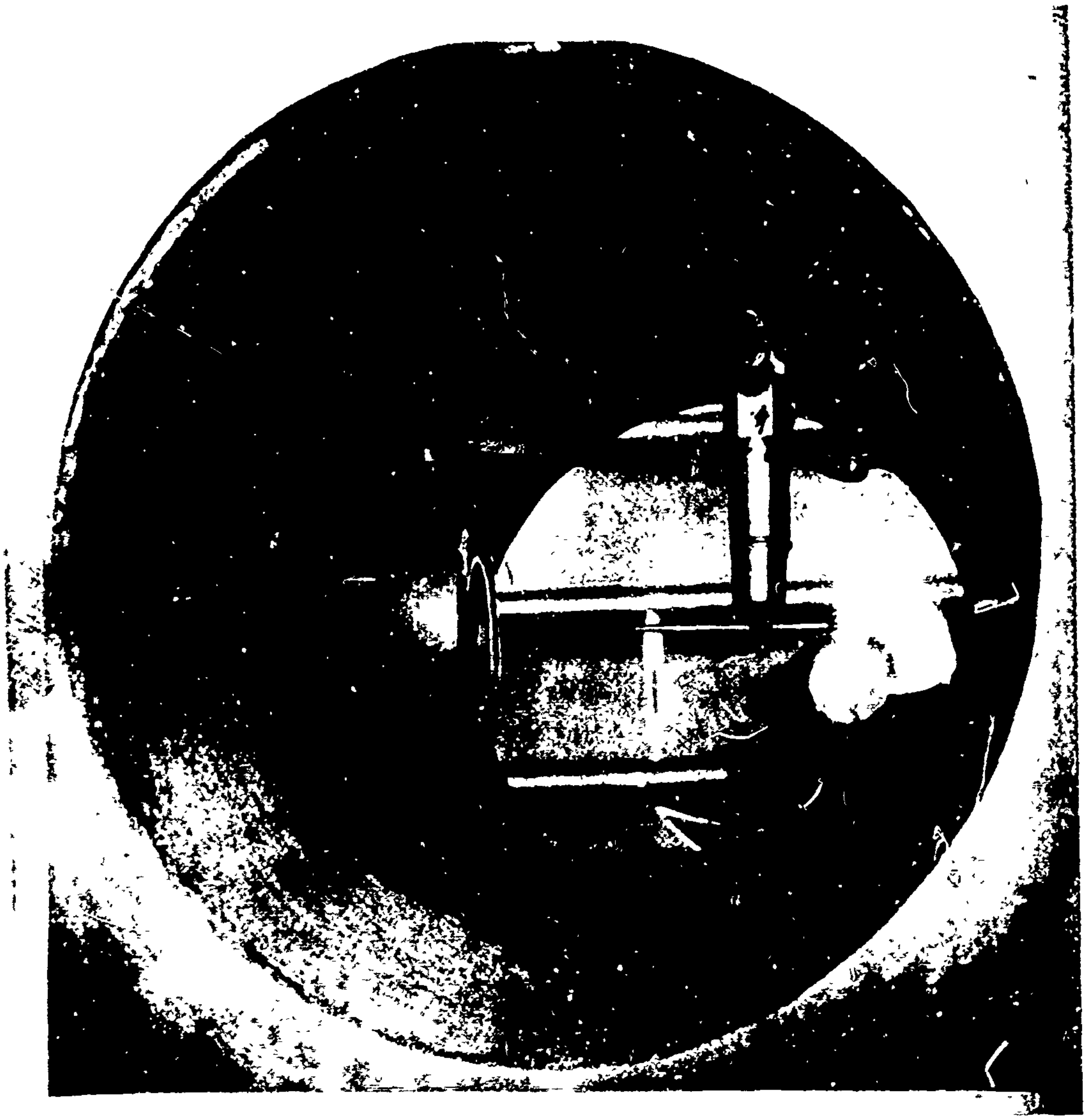

Fig. 1. Photograph of sampling probe and valve in shock tunnel.

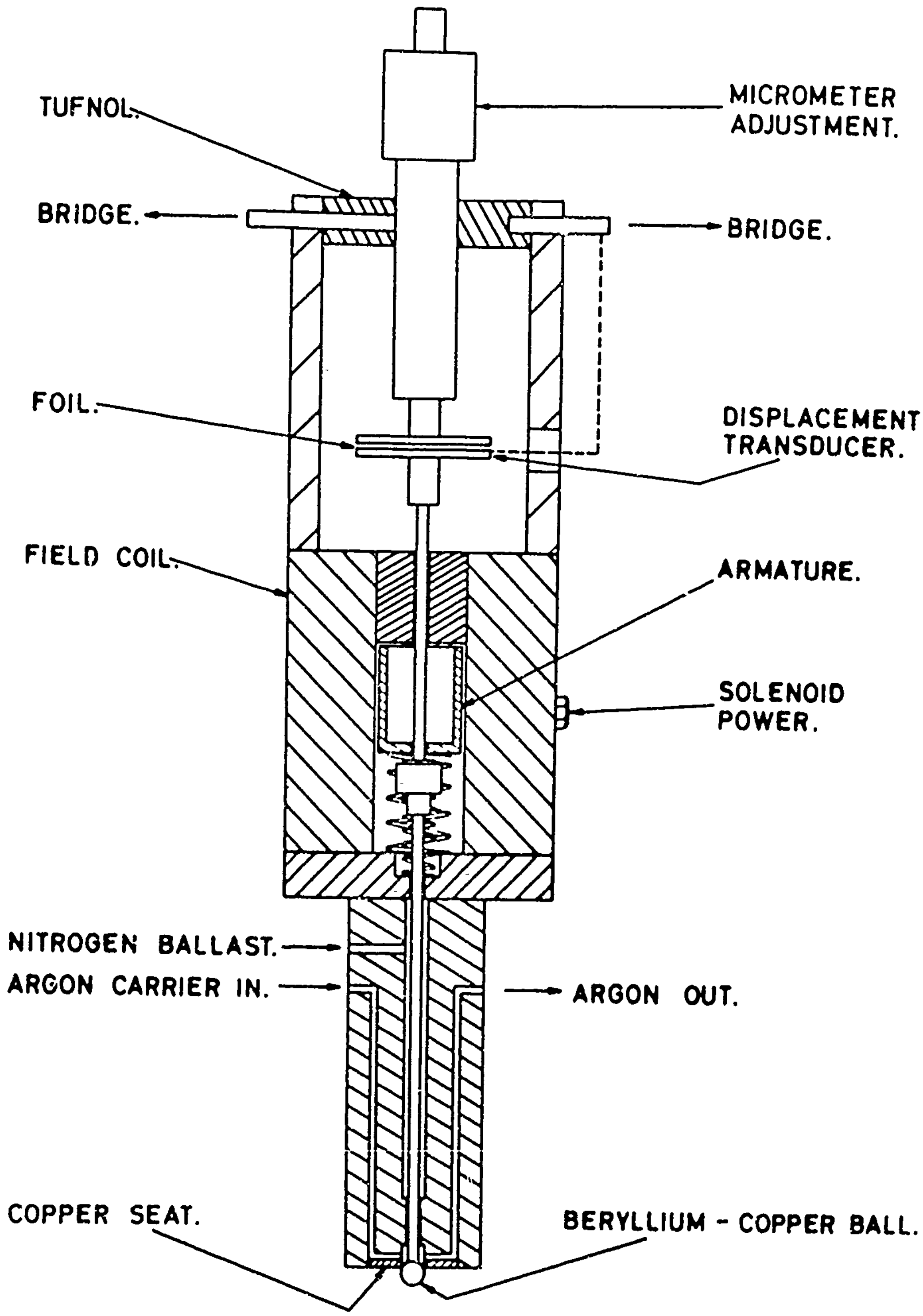

Fig. 2. Drawing of sampling valve.

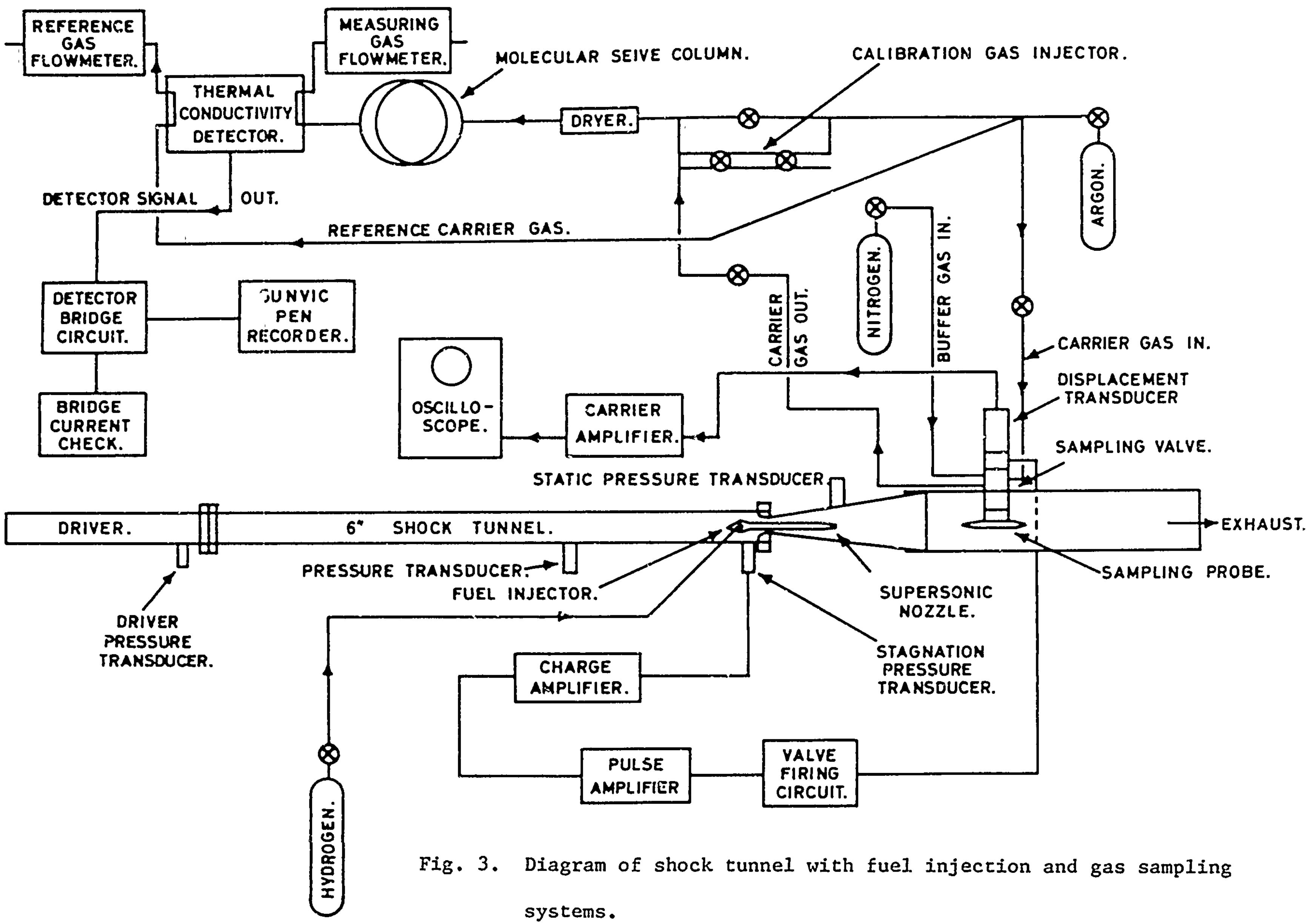

Fig. 3. Diagram of shock tunnel with fuel injection and gas sampling systems.

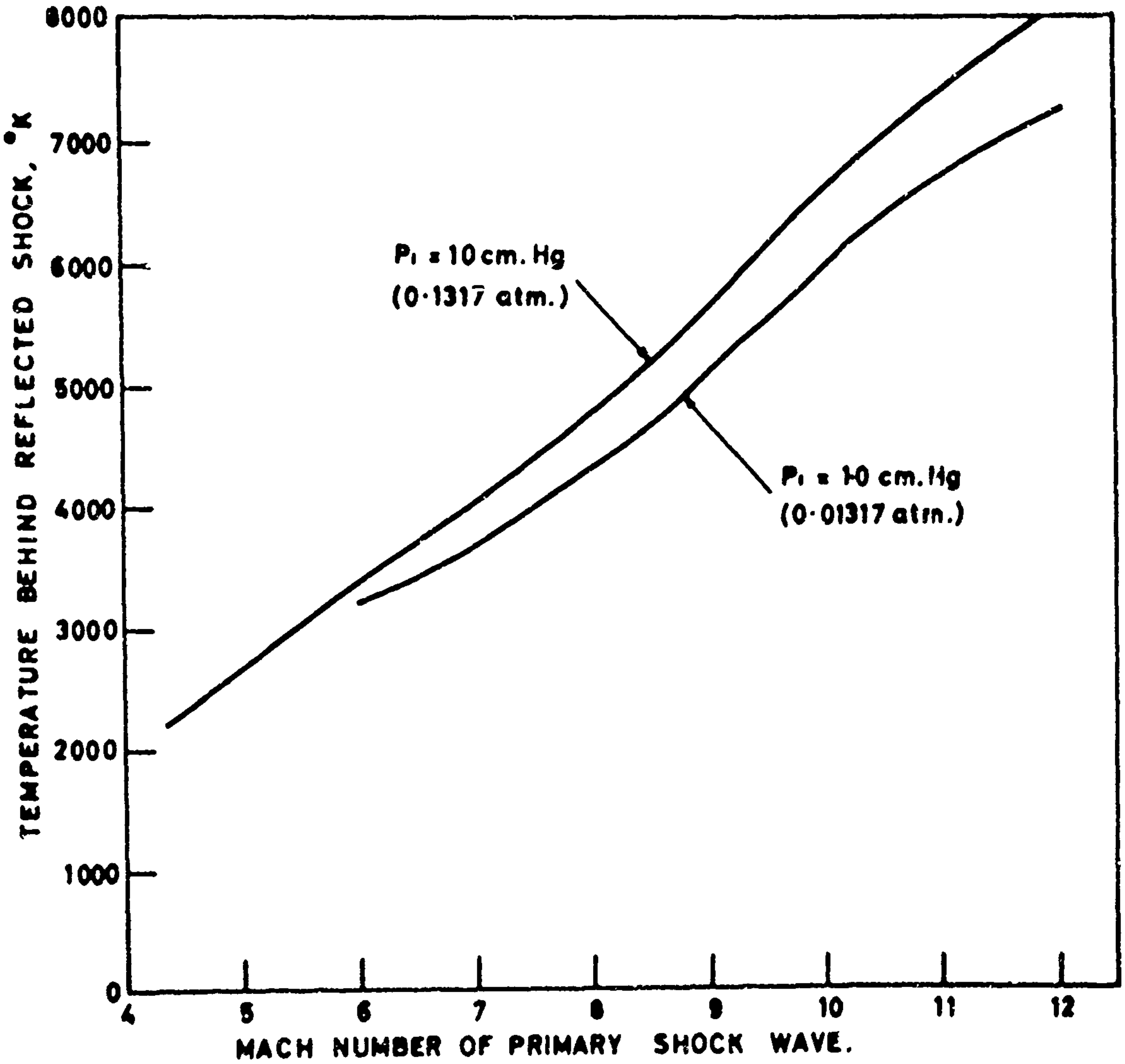

Fig. 4. Shock tunnel reservoir temperatures.

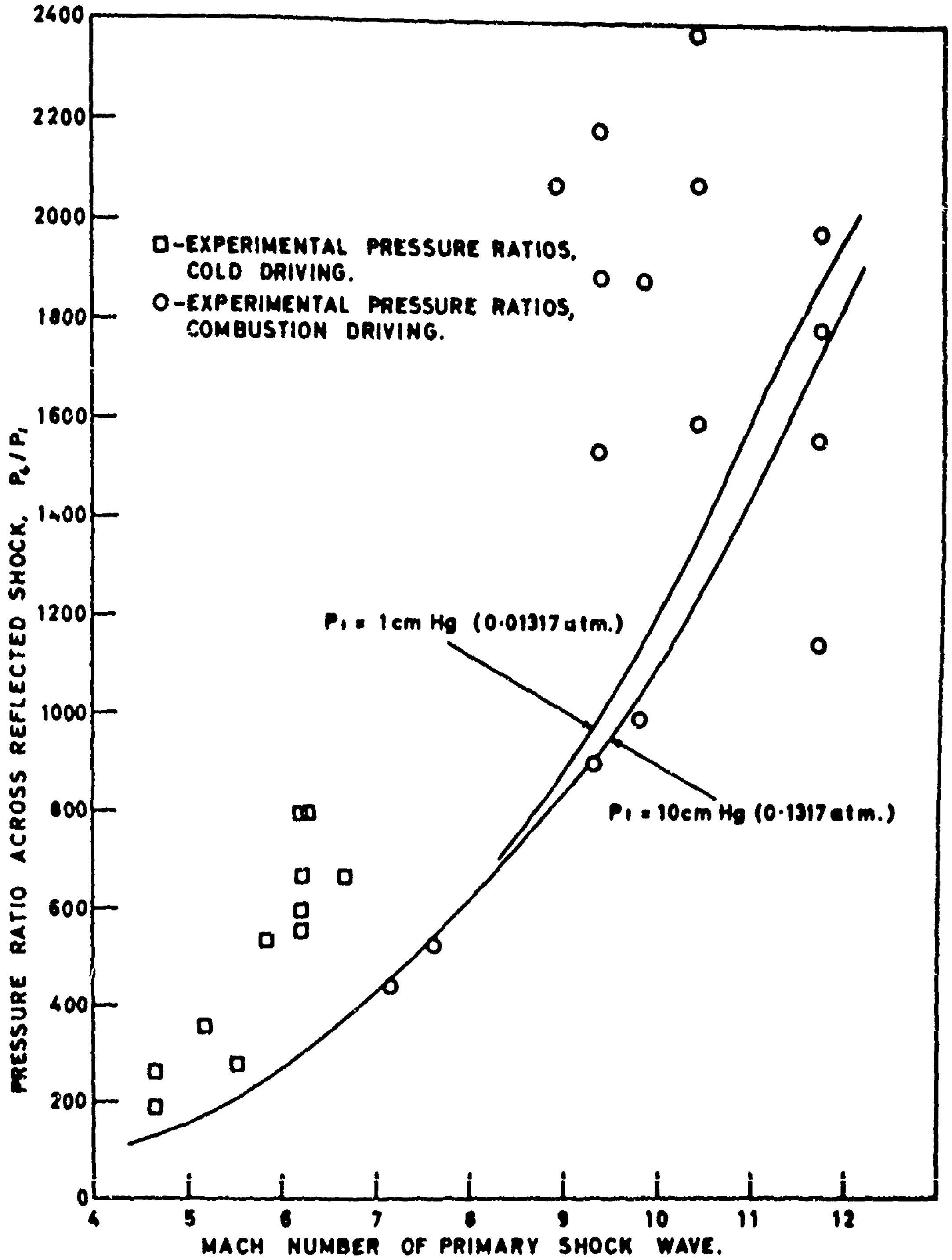

Fig. 5. Shock tunnel reservoir pressures.

against static pressure, static temperature, Mach number, and concentration of O_2, NO, and O, respectively, in Figures 6-11. Also noted on these graphs are area ratios for nozzles designated M = 3,4, and 5, respectively, designed for a flow of perfect gas. It will be noted that the theory predicts equilibrium flow under all conditions for the nozzle designated "M = 3" used in these experiments, but not so for the other two nozzles. Concentrations are referred to N_2, to permit comparison with experiment. It should be noted that considerable equilibrium concentrations of NO and deficiencies in O_2 are predicted.

Gas Pressure and Sampling Results

As mentioned earlier, necessary conditions for shock tunnel simulation of combustion chamber conditions include a usable testing time at constant pressure free of driver gas contamination, with gas composition representative of air which has undergone supersonic diffusion only. Pressure records with combustion, as well as with cold driving (near tailored conditions), indicated pressure plateaus from 1 to 1.5 milliseconds, after an initial starting disturbance of 0.5 to 1.0 millisecond. But driver gas appeared in almost every sample, indicating its early arrival. Driver gas concentrations as a function of time after shock reflection are shown in Figure 12, with nonreacting contact surfaces, i.e., helium driving into air, and hydrogen into nitrogen. Samples were taken along the centerline of the shock tunnel. The length of the horizontal bars represents the time interval during which the sampling valve was open.

Measured values of oxygen concentration vs. area ratio, compared

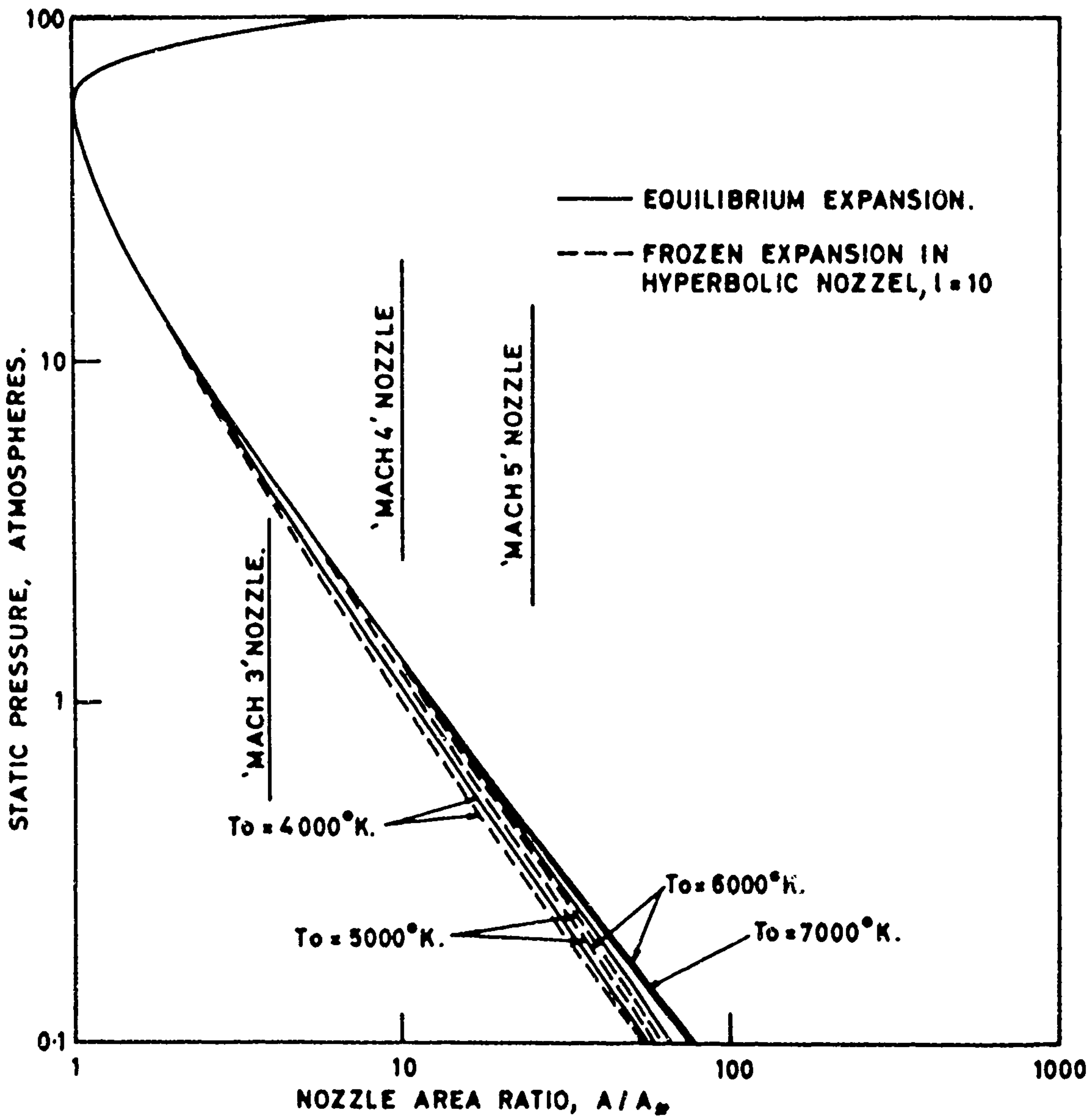

Fig. 6. Static pressure vs. area ratio.

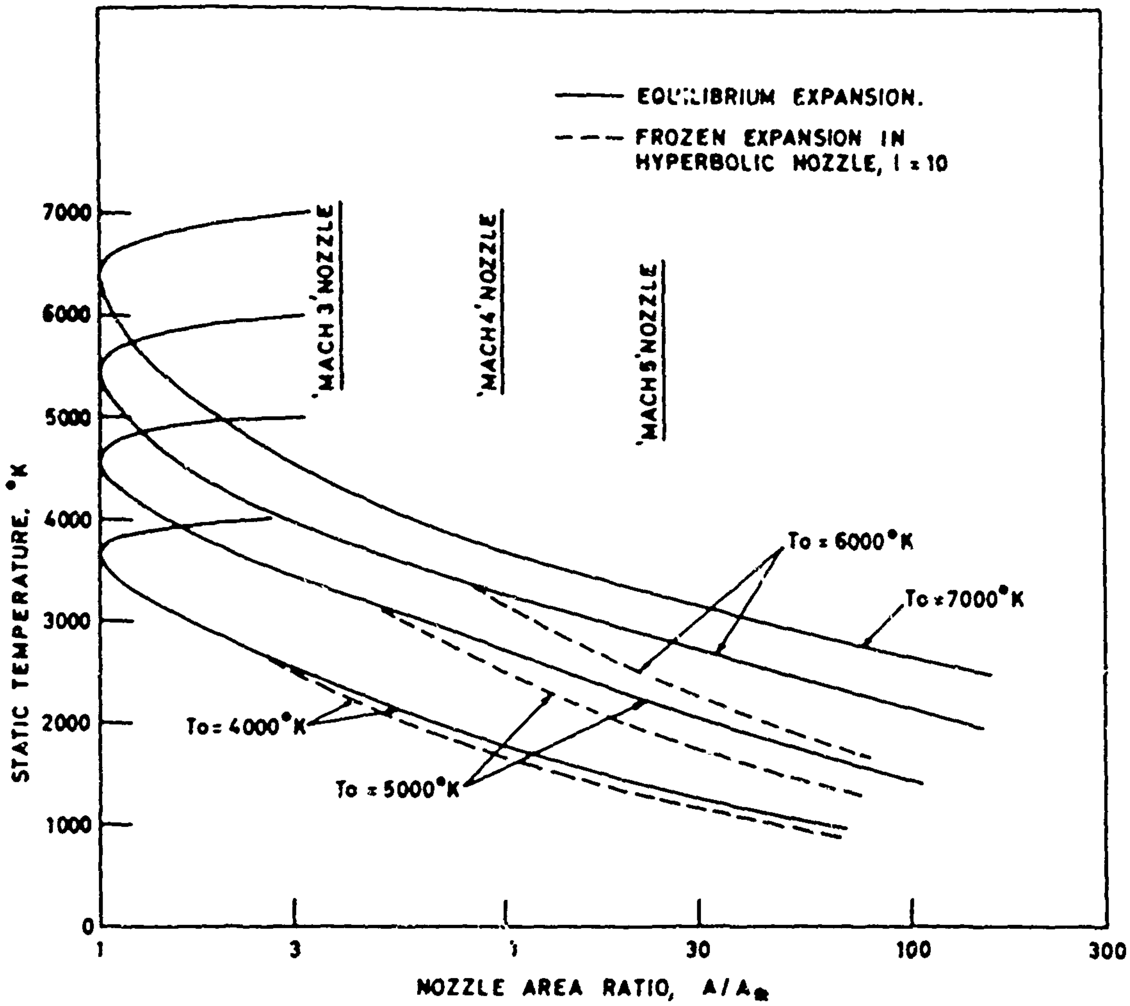

Fig. 7. Static temperature vs. area ratio.

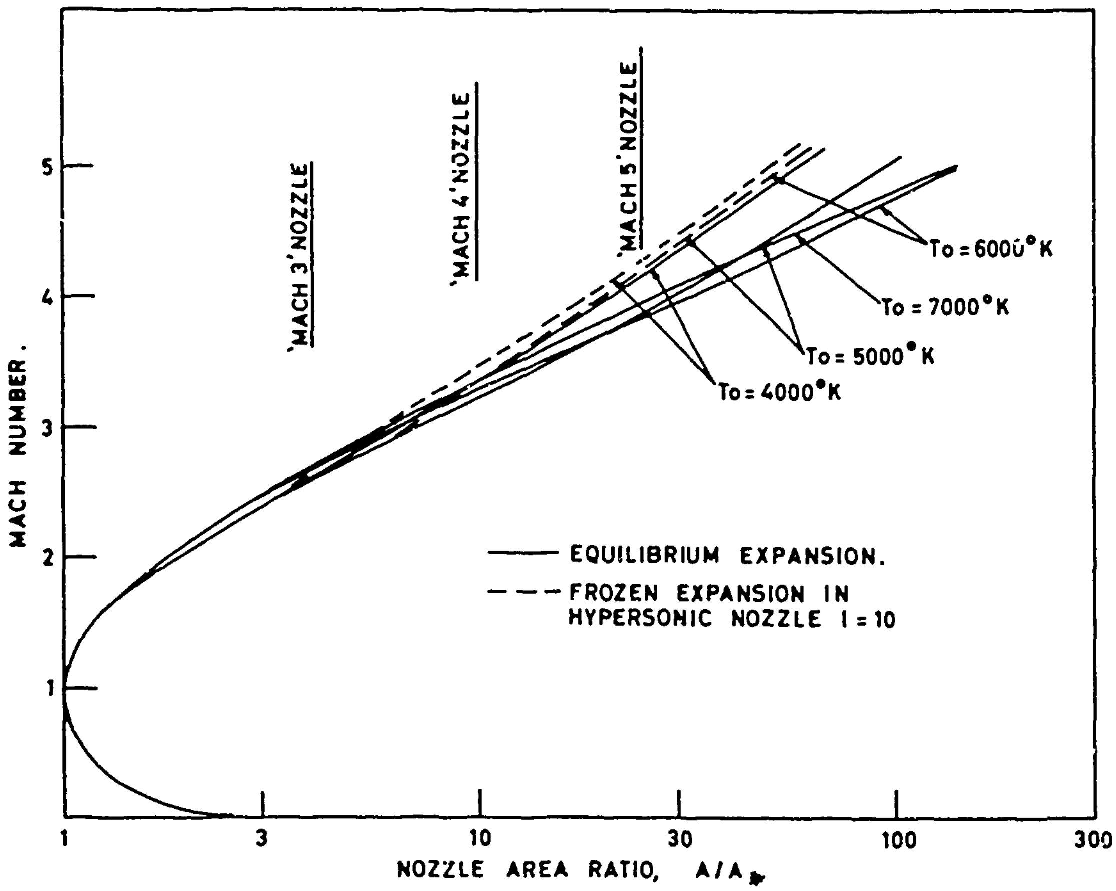

Fig. 8. Mach number vs area ratio.

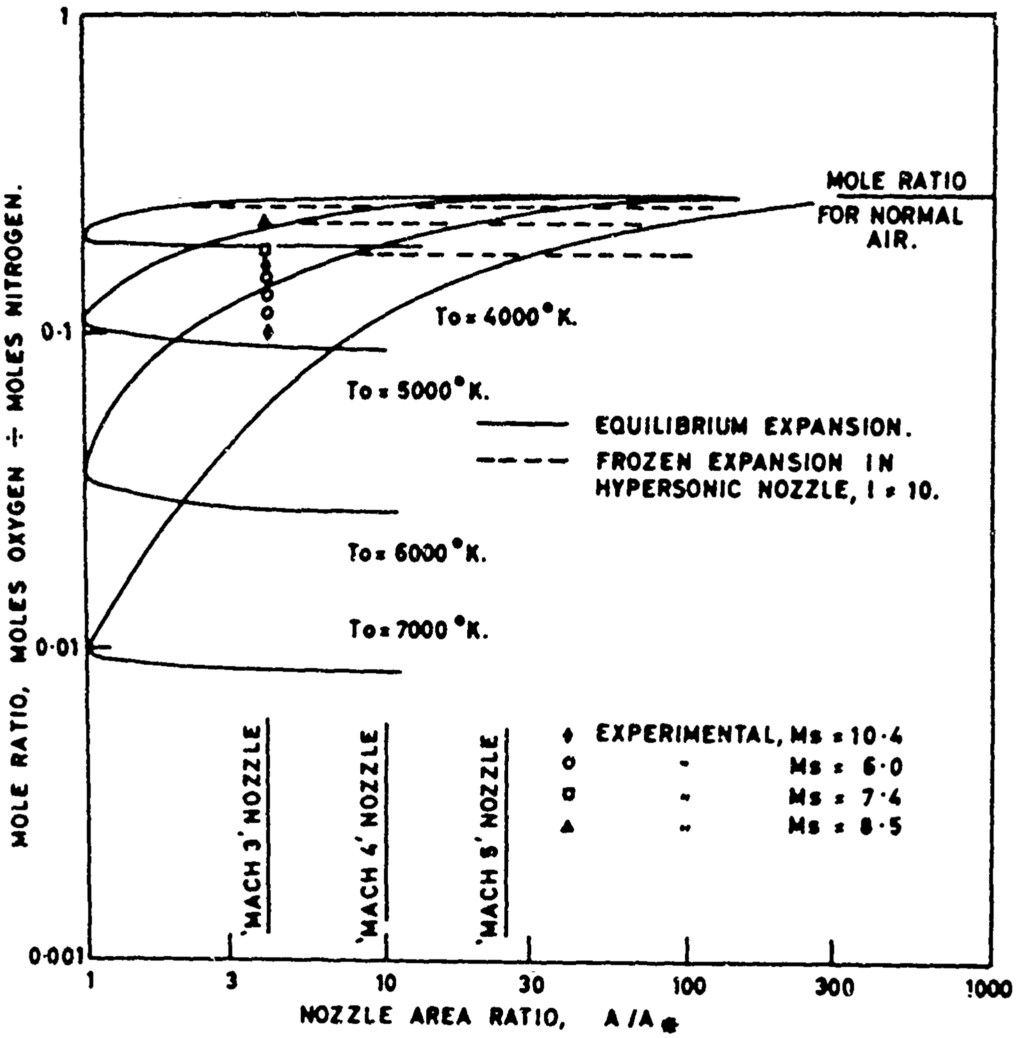

Fig. 9. Oxygen molecule concentration vs. area ratio.

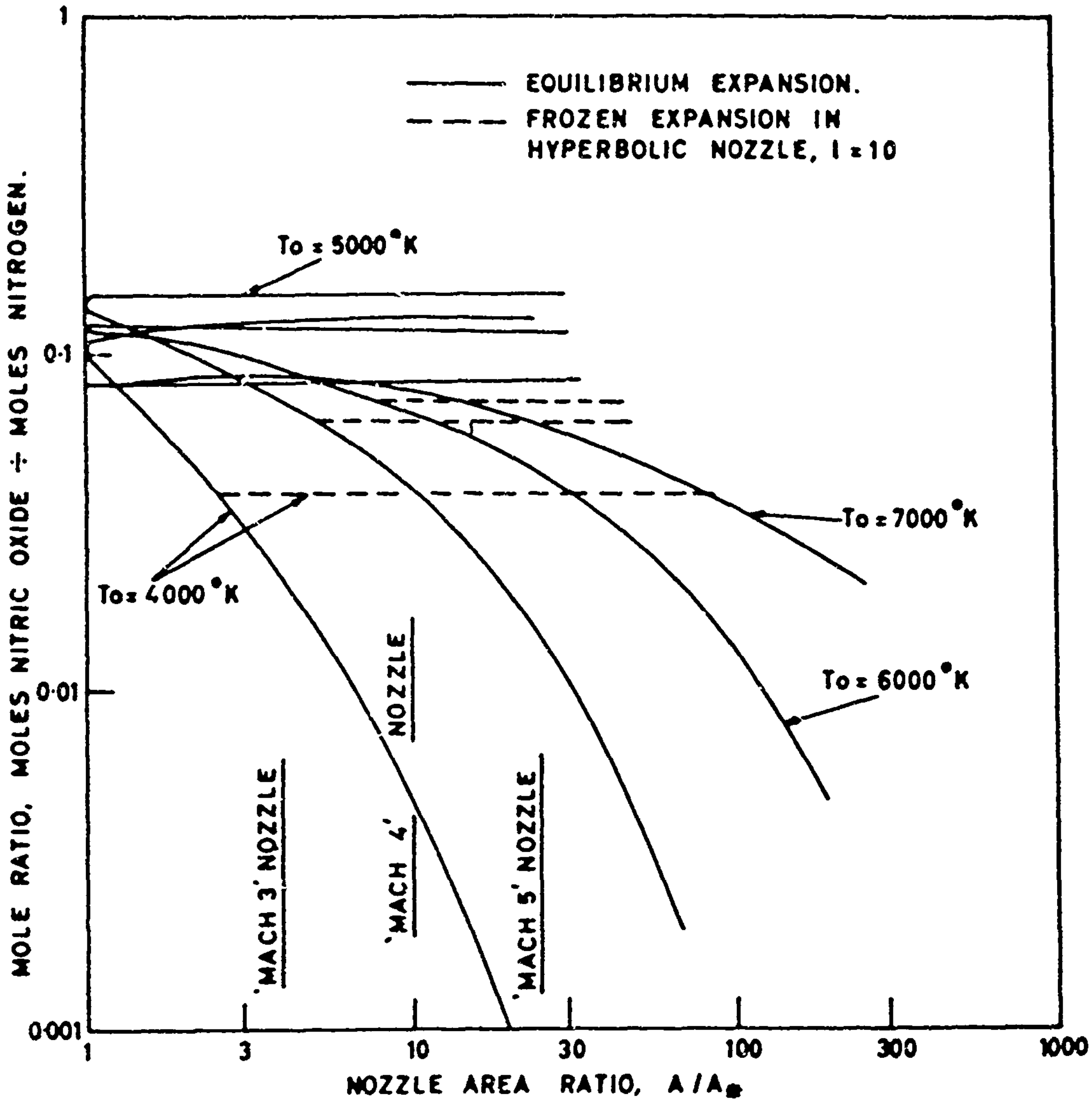

Fig. 10. Nitric oxide concentration vs. area ratio.

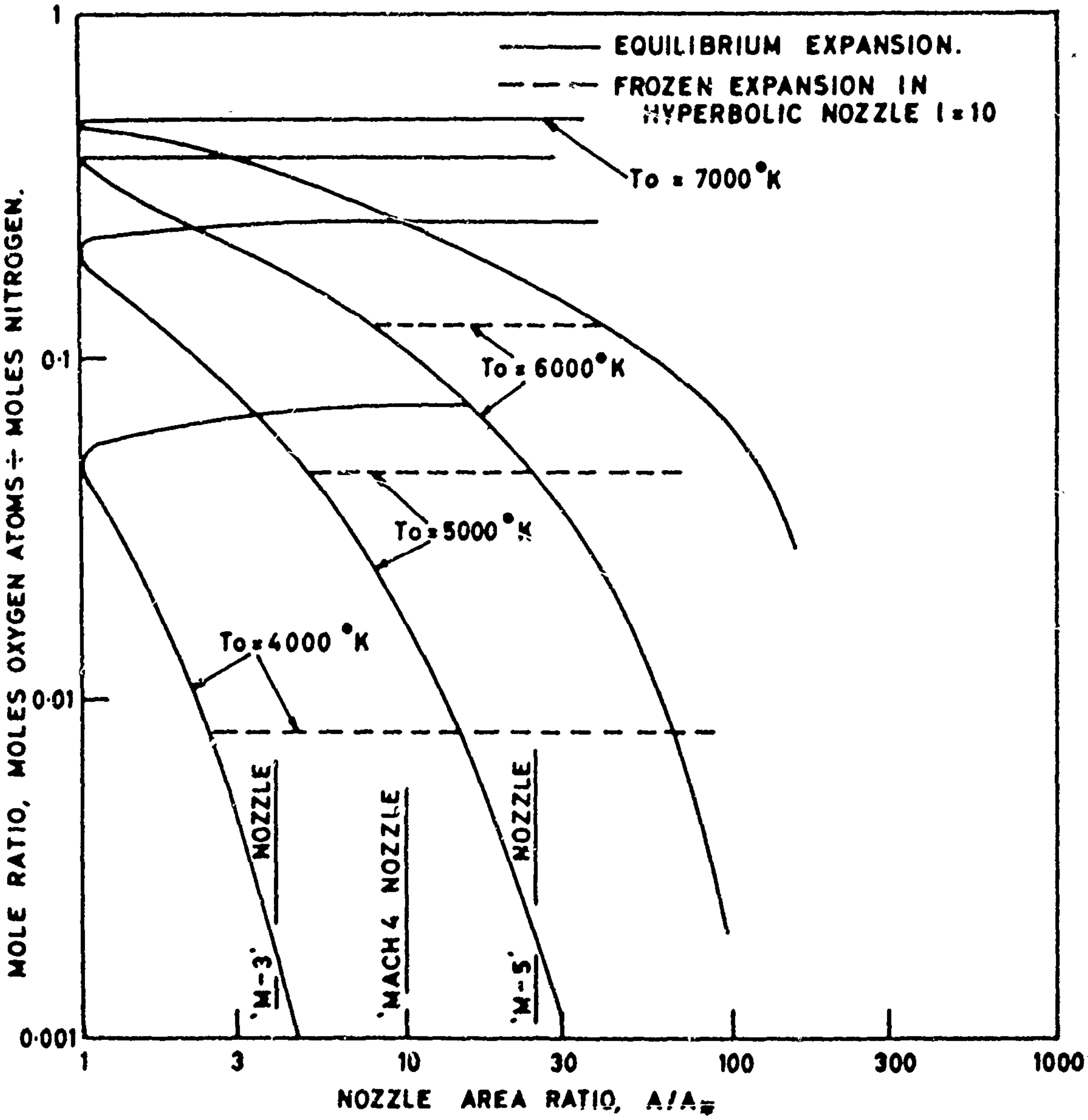

Fig. 11. Oxygen atom concentration vs. area ratio.

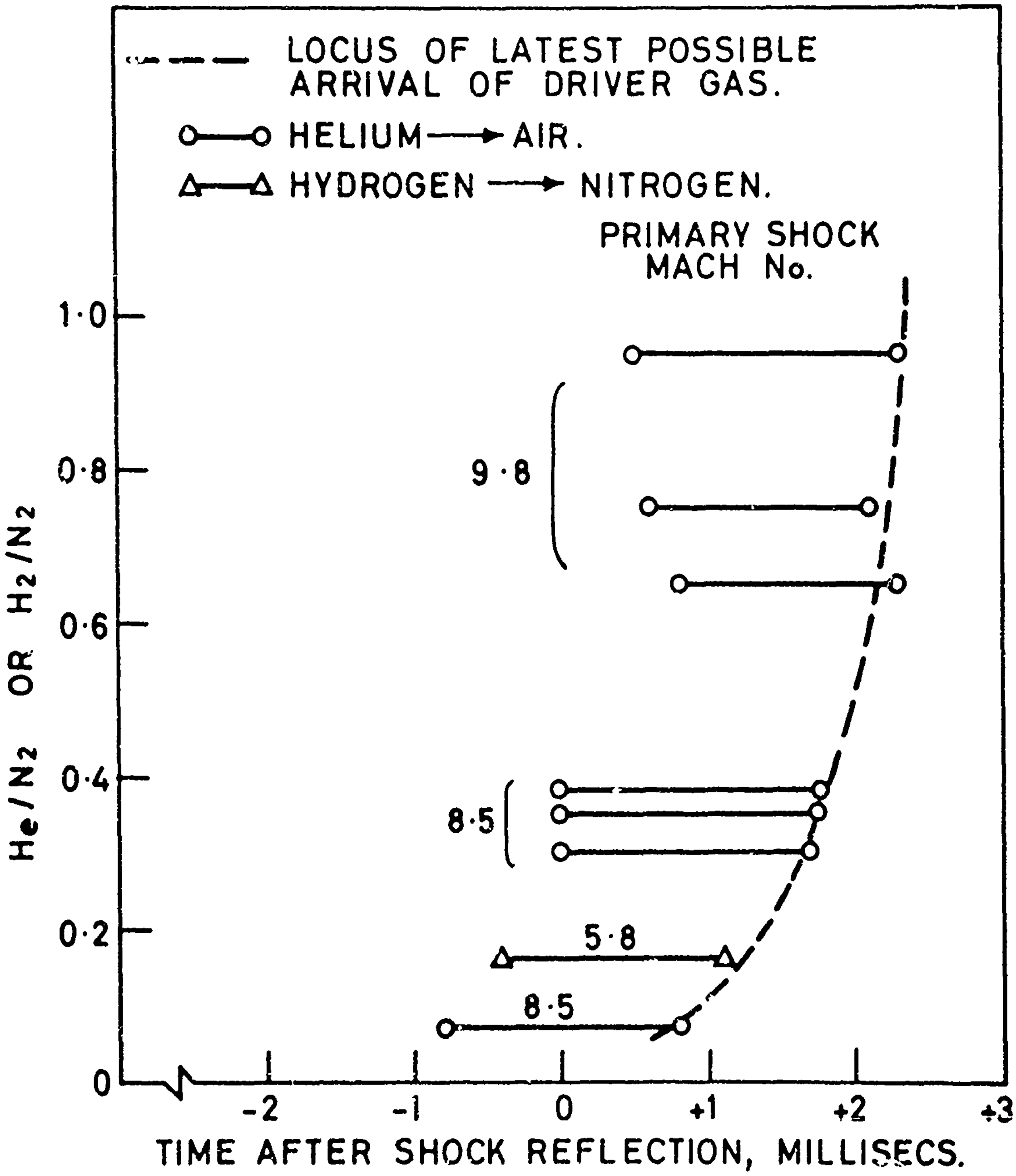

Fig. 12. Contamination of test air by driver gas.

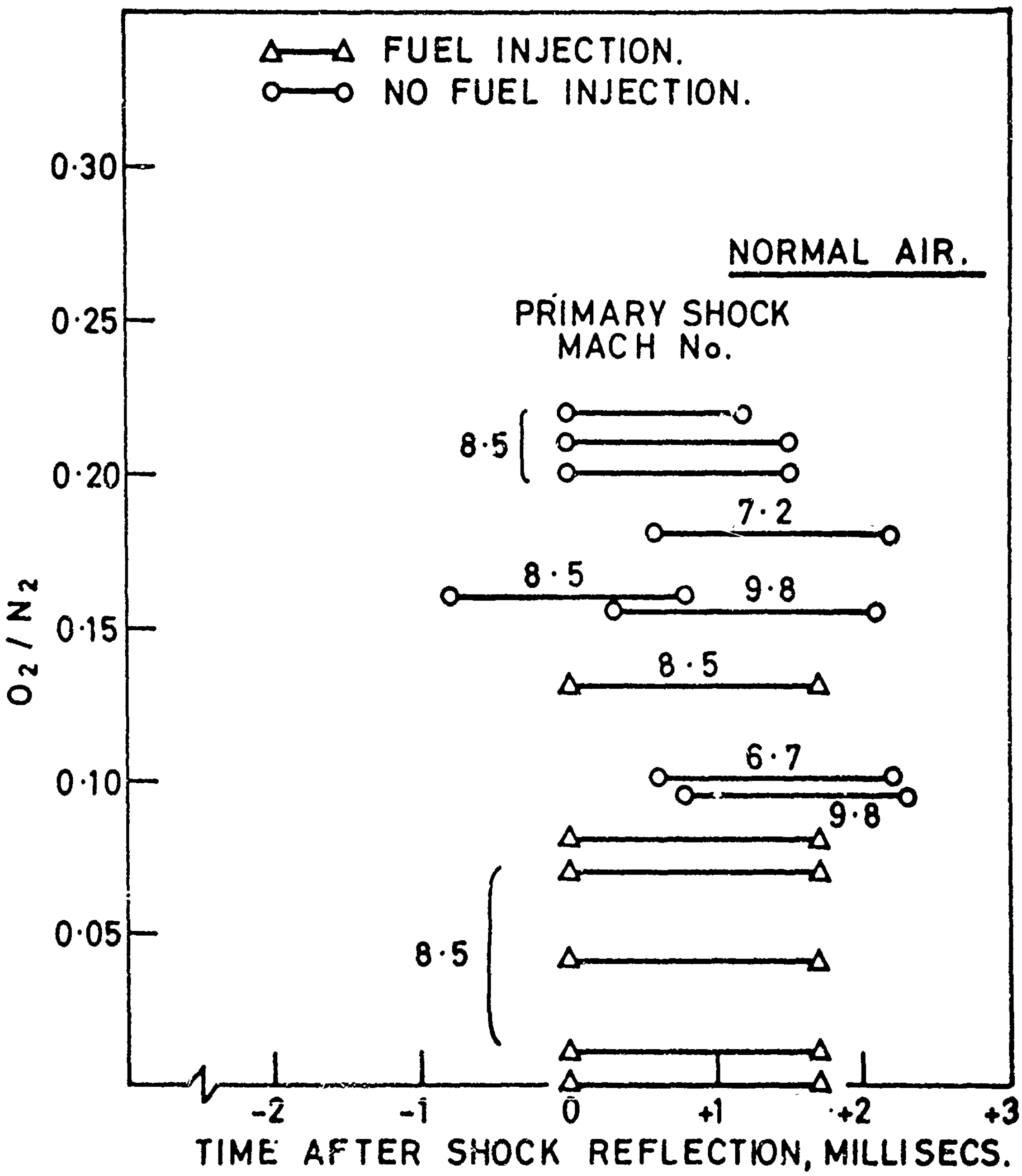

Fig. 13. Effect of fuel injection on oxygen concentration.

to predictions and to normal air, in the absence of fuel injection, are shown in Figure 9. Oxygen concentrations are also plotted in Figure 13 as a function of time after shock reflection, both with and without fuel injection, to show the effects of supersonic combustion. Hydrogen concentrations under the former condition, although small, are meaningless, since the sampling probe could not quench the combustion reaction. When hydrogen was injected into nitrogen, the results were also difficult to interpret, because hydrogen and helium could not be separated completely in the column.

Discussion of Results

In spite of its obvious importance, the arrival of driver gas into the test region of shock tubes or shock tunnels is difficult to detect by methods other than sampling. The results of this work show that pressure records give no indication of driver gas contamination, and such contamination appears to be independent of interface tailoring. Workers at Cornell Aeronautical Laboratories[9] noted erratic heat transfer results early in the testing period. Gas sampling performed by these workers showed driver gas arrival correlated well with the erratic heat transfer results, although the latter gave no quantitative information. Copper[10] noted that interface combustion, when hydorgen was driven into air, increased the instability and mixing of the interface compared to the situation when hydrogen was driven into nitrogen. Other workers have noted the early arrival of driver gas by spectroscopic detection of a tracer gas such as CO_2 placed in the driver.

At least two mechanisms have been proposed to explain the pre-

mature arrival of driver gas. One is the contact surface instability model, wherein the diffusion and mixing of the interface can be promoted by combustion, or turbulent boundary layers, or erratic diaphragm bursting. The other mechanism is bifurcation of the reflected shock, wherein the reflected shock bifurcates under some conditions, when it passes through the boundary layer left by the incident shock. When this reflected shock meets the contact region, the latter passes more rapidly through the foot of the shock than through the normal portion, and rapidly reaches the end wall. Davies[11] has analyzed this mechanism and predicts the effect to be less at under-tailored conditions. Edwards[12], using spectroscopic detection of CO_2 tracer in the driver gas, reported that his results indicated that the bifurcation mechanism was predominant. A more detailed discussion of driver gas contamination may be found in Reference 13.

Aside from possible driver gas contamination, we now consider the state of the test "air" in our shock tunnel simulation. In order to obtain a useful testing time, we must operate the shock tube at or slightly under tailoring conditions, so that, with hot driving, the reservoir temperature will be of the order of 6000°K. Under these conditions, considerable equilibrium concentrations of NO and dissociation of O_2 will exist. If we expand this gas with an area ratio ≤ 10, we find the equilibrium static temperatures too high for simulation, with still large amounts of NO and O. But if we expand this gas further for an area ratio ≥ 10 (combustion chamber $M \geq 3$), with a practical nozzle, we find that the flow freezes, anyhow, and we still fail to simulate the desired air composition. The experimental results quoted above always indicated

an O_2 concentration considerably less than normal air. Although it is true that the oxygen atoms will recombine in the sampling system, the residence time is long enough for most of the NO to react with O_2 to form NO_2 and leave us with about the right amount of O_2 remaining. One way to relieve the problem would be to operate considerably under-tailored (lower temperatures) even though the testing time would be shorter. The latter condition also relieves somewhat the shock bifurcation problem. It has also been suggested that an inert gas such as argon be substituted for nitrogen, even though the expansion process would be drastically changed. Chambers[1] reported the effect of small amounts of NO in H_2-air mixtures on the ignition time delay at temperatures less than 1000°K. The ignition delays with NO present were an order of magnitude less than those for H_2 and air alone.

The results of Figure 13 indicate that most of the remaining oxygen was consumed when hydrogen was injected. The sampling also showed negligible amounts of hydrogen, indicating that both mixing and combustion were nearly complete, but how much occurred in the probe is difficult to determine at this stage. Separate measurements indicated that the swirl generator placed in the fuel injector was quite effective in producing swirl, but it was difficult to assess how this affected the mixing, because the presence of driver gas and of combustion masked the analysis.

Conclusions

Gas sampling techniques provide a very useful tool in assessing the ability of a shock tunnel to perform realistic simulation of supersonic

combustion chamber conditions. Clear indications of driver gas contamination are indicated, in contrast with pressure records alone. In addition, valuable information can be obtained as to the composition of the test "air" as well as details of supersonic mixing and combustion. Most of the nonequilibrium effects referred to, such as excessive static temperature and pressure and NO concentrations, tend to shorten the kinetics, compared to the situation for equilibrium flow. These nonequilibrium and "odd" gas compositions have less effect on mixing and heat transfer.

Acknowledgements

We wish to express our appreciation to Professor J. M. Beer, of the Department of Fuel Technology and Chemical Engineering, University of Sheffield, for his support and encouragement for this work, and to Mr. L. Mellor for his assistance with the experiments. We are also grateful to Mr. D. H. Desty and associates, of the British Petroleum Research Center, for their assistance with the rapid sampling valve.

References

1. Chambers, H. F., Jr., "Analytical Study of Shock Tunnel Simulation of Combustor Entrance Conditions", Tech. Report AFAPL-TR-66-82, Air Force Aero Propulsion Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio (AD-646 599), October 1966.

2. Swithenbank, J. and Parsons, R. J., "Experimental Techniques for Supersonic Combustion Research in a Shock Tunnel", presented at the 30th Propulsion and Energetics Panel Meeting on "New Experimental Techniques in Propulsion and Energetics Problems", Munich, Germany, September, 1967 (AD 670 609).

3. Osgerby, J. T., Ph.D. Thesis, Department of Fuel Technology and Chemical Engineering, University of Sheffield, October 1965.

4. Wood, M. P., Ph.D. Thesis, Department of Fueld Technology and Chemical Engineering, University of Sheffield, August, 1968.

5. Parsons, R. J., Ph.D. Thesis, Department of Fuel Technology and Chemical Engineering, University of Sheffield, 1969.

6. Richmond, J. K. and Parsons, R. J., "Application of Rapid Sampling Techniques to Supersonic Flows of Gas Mixtures in a Shock Tunnel", Report No. H.I.C. 118, Department of Fuel Technology and Chemical Engineering, University of Sheffield, September 1968.

7. Feldman, S., "Hypersonic Gas Dynamic Charts for Equilibrium Air", AVCO Research Laboratory, January 1957.

8. Boyer, D. N., Eschenroeder, A. Q. and Russo, A. L., "Approximate Solutions for Nonequilibrium Airflow in Hypersonic Nozzles", Cornell Aeronautical Laboratory, Inc. AEDC-TN-60-181, August, 1960.

9. Martin, J. F., "Investigation of Test Time at Under-Tailored Conditions in a Shock Tunnel", Cornell Aeronautical Laboratory, Inc., Report No. WTH-026, May 1963.

10. Copper, J. A., "Effects of Interface Combustion and Mixing on Shock-Tunnel Conditions", AIAA Journal 2, No. 9, 1669-1671, September 1964.

11. Davies, L. and Wilson, J. L., "The Influence of Shock and Boundary Layer Interaction on Shock Tube Flows", NPL Aero Report 1228, ARC 29064, Hyp. 615, 4 May 1967.

12. Edwards, D. H., "Infra-red Studies in a Shock Tube", 18th Shock Tube Liaison Meeting, Imperial College of Science and Technology, April 25, 1968.

13. Richmond, J. K. and Parsons, R. J., "Driver Gas Contamination in Shock Tunnels", delivered at the 21st Annual Meeting of the Division of Fluid Dynamics, American Physical Society, Seattle, Washington, November 25-27, 1968; Bulletin of the American Physical Society, Series II, Volume 13, Number 11, November 1968, p. 1603.